

Sequential heuristic optimisation of a real offshore wind farm site considering turbine placement and cable layout

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Abstract. Competition within the energy generation industry provides an incentive for developers to build offshore wind farms with a low levelised cost of energy. Therefore, there is a need for design optimisation to reduce costs and increase energy capture. A sequential approach to optimise turbine placement and cable layout is presented, using a heuristic k-opt algorithm and mixed-integer linear programming respectively. Energy storage is considered as a means to further improve the cable selection process. A case study is carried out on the Lillgrund offshore wind farm and the resulting layout improves energy capture by 6%. Cable costs are increased but the electrical losses are reduced such that there is an overall saving over the project lifetime of 20%. Energy storage as a means to peak shave the power seen by a cable in order to reduce electrical losses or de-rate a cable section was found to be impractically large and not profitable. Future work will consider secondary revenue streams to remedy this.

1. Introduction

As interest continues to grow in the renewable energy industries, offshore wind energy has commanded a large share of the attention, particularly in Europe. Projections for the sector indicate large growth over the coming decades and agreements such as the UK Sector Deal for Offshore Wind will only strengthen these predictions, bringing more certainty - and with it, more investment.

Competition with other types of generation and also within the industry itself provides an incentive for developers to build offshore wind farms (OWFs) with a low levelised cost of energy (LCOE) amongst other design factors. As such, there is a need for the designs of OWFs to be optimised, reducing costs (both capital expenditure (CAPEX) and operation and maintenance expenditure (OPEX)) and increasing energy capture.

Several studies have looked into the optimisation of various stages of the design of an OWF and can broadly be grouped into two categories: turbine placement optimisation and sub-sea cable layout optimisation. In 1983, Jensen [1] developed a model for estimating the effect of



a turbine wake on another downstream turbine. This has since been built upon and used by many studies including: Katic et al [2] who proposed a method for the summation of the effects of multiple wakes acting on a turbine, and Larsen [3] who developed a kinematic model based on the Prandtl turbulent boundary layer equation with non-linear wake expansion and a radially varying wake effect. These models, and others, have been used to try and position turbines within a wind farm such that the wake effect - and therefore reduction in power - can be minimised. Mosetti et al [4] was among the first to do this, placing turbines in a 10x10 grid layout using a genetic algorithm (GA) with variable wind direction and intensity. Other studies have used various approaches including other evolutionary algorithms [5, 6, 7, 8, 9, 10] as these are more suited to the high dimension and greater complexity of the problems being solved. Linear programming solvers have also been used but on reduced, simplified problems and often seeded with a heuristic solution [11, 12].

The electrical infrastructure of an offshore wind farm is a significant cost in the total CAPEX of the project at around 10-30% [16]. A large proportion of this comes from the collector network array. As such, different collector network layout designs and configurations became of increasing interest as explored by Quinonez-Varela et al [13] in 2007. Integrated optimisation of turbine positioning and cable layout was considered by González et al [7] in 2011 with the use of two nested evolutionary algorithms. Since then many studies have attempted to minimise the total cable length with alternative optimisation algorithms. These include particle swarm optimisation (PSO), ant colony optimisation (ACO) and mixed-integer linear programming (MILP) models [10, 14, 15, 16, 17] and often take into account penalties from branching nodes, cable capacity limits and electrical losses as factors for optimisation. Energy storage may also be able to offer benefits in providing relief to de-rated networks with smaller, and therefore cheaper, cables.

This study presents a quick, sequential heuristic optimisation based on the Lillgrund OWF off the coast of Sweden. The following, section 2, covers the methodology of the approach, including: a heuristic turbine placement optimisation (section 2.2), a mixed-integer linear programming solver for cable layout optimisation (section 2.3) and consideration of energy storage to allow for the selection of de-rated cables in the solution (section 2.4). Further, results are presented in section 3 and the effectiveness of the optimisation is discussed. Future models to OWF optimisation are proposed in section 4.1.

2. Methodology

A sequential optimisation is proposed that includes three stages of optimisation, in which each stage of the optimisation can be considered independently:

- (i) Turbine placement optimisation
- (ii) Cable layout optimisation
- (iii) Energy storage optimisation (for cable re-selection)

The turbine placement optimisation places the turbines in the best positions it can find aiming at maximising power output. These positions are passed onto the cable layout optimisation. Although feedback from the cable layout optimisation phase may be useful in influencing the positions of turbines, this is not covered in this study. The cable layout algorithm minimises the total cost of cables, installation and electrical losses. Energy storage is then considered as an option for selecting de-rated, cheaper cables.

2.1. Lillgrund offshore wind farm case study

In order to provide a comparison of the optimisation result to a real-world case, the Lillgrund OWF was used as the site on which to run the optimisation algorithm. The real wind farm was

also analysed with the same models to assess annual energy production, electrical losses and approximate costs of the array cable network.

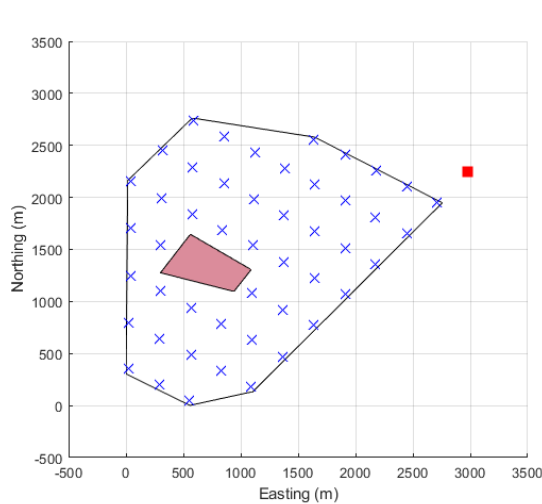


Figure 1. Lillgrund OWF site

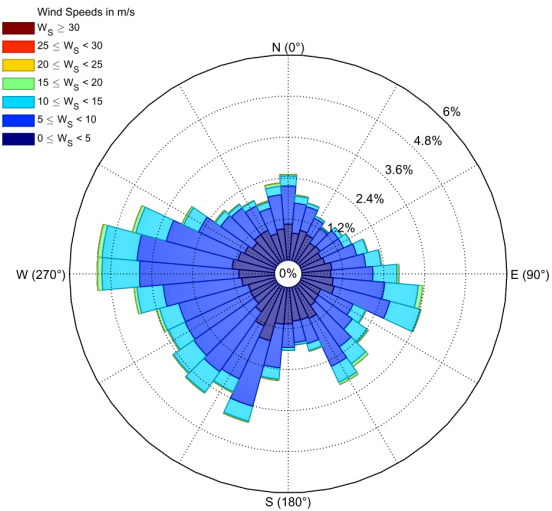


Figure 2. Wind rose for OWF [18]

Figure 1 shows the wind farm area with the real turbine positions marked with an ‘x’ and the substation marked by a ‘■’. An approximated area of possible turbine positions is outlined, and the shaded red area within the wind farm represents an area inaccessible to vessels due to shallow water caused by a shipwreck. The wind farm contains 48 Siemens SWT-2.3-93 turbines, each rated at 2.3MW, resulting in a wind farm rated power of 110.4MW. It is laid out in a standard grid formation with rows and columns spaced at 4.3 and 3.3 rotor diameters respectively. Figure 2 shows the wind rose of the nearby Middelgrunden wind farm from [18] based on time series data from 2001-2004. Although not identical, this wind rose is representative of the wind conditions at the Lillgrund site. Average wind speeds across binned wind directions (of 30°) measured at the Lillgrund site were used in this study.

2.2. Turbine placement optimisation

The wind farm is discretised into nodes on which the algorithm can choose to build a turbine or not. In this study the maximum east-west distance and maximum north-south distance of the wind farm were measured and divided by 100 to give a grid of 100×100 possible turbine positions to be considered. Any points outside of the defined wind farm area or within the forbidden region were removed resulting in 6165 possible turbine positions with a spacing of 27.55m and 27.62m in the east-west and north-south directions respectively. An ‘interference matrix’ was calculated using the Jensen model [1] in a pre-processing phase that calculated the wake effect of a node on every other node if a turbine were to be built on both. The wind directions input to the model were binned with an accuracy of 30° with each bin being broken down by the model into equal 5° increments to better evaluate the wake effects. With such a fine resolution the problem is very large and so the pre-computation phase can take a relatively long time, in this case ~ 22hrs on a standard desktop PC (3.4GHz Intel Core i7-6700, 16GB RAM). This does not need to be recomputed for any further studies unless the wind farm, wind or turbines are changed.

The algorithm is a simple, and fast, *k-opt* algorithm. At each iteration of the algorithm, every node is analysed to find the effect of a ‘flip’. As the solution is a binary string of 0’s and

1's representing if a turbine is absent or present at each node, a flip represents changing a $0 \rightarrow 1$ or a $1 \rightarrow 0$. For the 1-opt algorithm this means assessing the effect of every individual flip to find the best flip, for the 2-opt this means assessing every possible pair of flips. On finding the best option the flip is performed and the variables updated. For the outlined process below with 6165 nodes the computational time was approximately 20 minutes on a PC with specifications mentioned previously.

Turbine placement k-opt heuristic outline:

- (i) **1-opt algorithm** Add turbines while it is profitable to do so (in terms of wind farm power)
- (ii) **1-opt algorithm** Force solution to move from local optimum (*up to 1000 iterations*)
- (iii) **2-opt algorithm** Locally adjust turbines of best solution found with (*500 iterations*)
- (iv) Repeat (ii) (*100 iterations*)
- (v) Repeat (iii) (*100 iterations*)
- (vi) Repeat (ii) (*100 iterations*)
- (vii) Repeat (iii) (*200 iterations*)

2.3. Cable layout optimisation

Upon receiving turbine positions from the placement algorithm the cable layout algorithm generates all possible arcs between all nodes (substation(s) and turbines) and reduces this down to reduce the model size. It achieves this through only allowing a turbine to connect to the nearest N nodes, in this study the nearest 6 nodes. The provided cable types are broken down into 'sub-types' to consider each cable under different conditions i.e. supporting 1, 2, 3..max turbines. These sub-types are considered by the model as separate cable types and the electrical losses per metre of cable are calculated during pre-processing. Electrical losses are calculated based on the average power experienced by a cable section over a 25 year project lifetime, and discounted into net present value terms to be included with the cable unit price. Installation costs per metre of cable are included and are the same for all cable types in this study. As the model tries to select the cheapest cable option for each arc that is built, the higher electrical losses of a cable supporting more turbines than necessary deters the model from selecting it. Constraints stating that the cable capacity cannot be below the number of turbines being supported ensure that the correct, and cheapest possible, cable is selected for each arc. The formulation of the problem consists of binary variables, stating if a given type of cable is built on a given arc section or not, and continuous variables, describing the power flow experienced by a cable section. The presence of both discrete and continuous variables for optimisation constitutes a mixed-integer problem and so requires a suitable solver, capable of dealing with this sort of problem.

The solver used is a built-in Matlab MILP solver, *intlinprog*. The key steps of this solver are:

- (i) Reduce problem size with linear programming (LP) pre-processing
- (ii) Solve an initial relaxed (non-integer) problem with LP
- (iii) Tighten the LP relaxation with mixed-integer program pre-processing
- (iv) Further tighten the LP using cut generation
- (v) Find integer-feasible solutions using heuristic approaches
- (vi) Branch and bound algorithm to solve a restricted formulation of the LP relaxation

2.4. Energy storage optimisation for de-rating cables

Energy storage can be used to smooth the power output seen in a cable by charging at times of high energy production and discharging during times of low energy production. In order to correctly size energy storage to provide the necessary power smoothing but at minimum cost the variability of power over time must be known. Figure 3 (top) shows the power produced by a string of 10 turbines over approximately 28 days selected from 4 years of real world wind speed data provided by the FINO1 research platform [19] in the North Sea. Although not specifically for the Lillgrund site, the time series data is indicative of real world conditions offshore and has a lower mean wind speed making the profitability of energy storage more likely than at the Lillgrund site. The largest saving to be made from de-rating a cable to the next sub-type is found by ‘de-rating’ from the sub-cable supporting 10 turbines to the sub-cable supporting 9 turbines, saving £858.10/m over 25 years. As these two different sub-types of cable are the same type of cable, these savings are entirely a result of reduced electrical losses over the project lifetime. This is because electrical losses increase non-linearly with current and so high power conditions, as seen by supporting more turbines, increases the losses by an ever-increasing amount for every additional turbine.

From the time series of power in the cable section to be de-rated, it is possible to integrate about the de-rated level (red line in figure 3 (top)) to show the required capacity of an energy storage system over time to achieve this level of de-rating, figure 3 (bottom). As would be expected for the majority of the time the required energy storage is relatively low with occasional large peaks at extended times of high wind speed. Figure 4 shows a continuous plot of the energy capacity required by the energy storage system (ESS) and the fraction of time that it would be able to maintain normal operation. Initially the minimum fraction of time acceptable was set to 0.95 which led to a minimum possible ESS size of around 157MWh. For any acceptable level of confidence that the network will be able to operate for a given period of time, the ESS size becomes impractically large, both in size and cost. For this reason the energy storage variable was no longer included in the optimisation process with the current set of available cables and turbines.

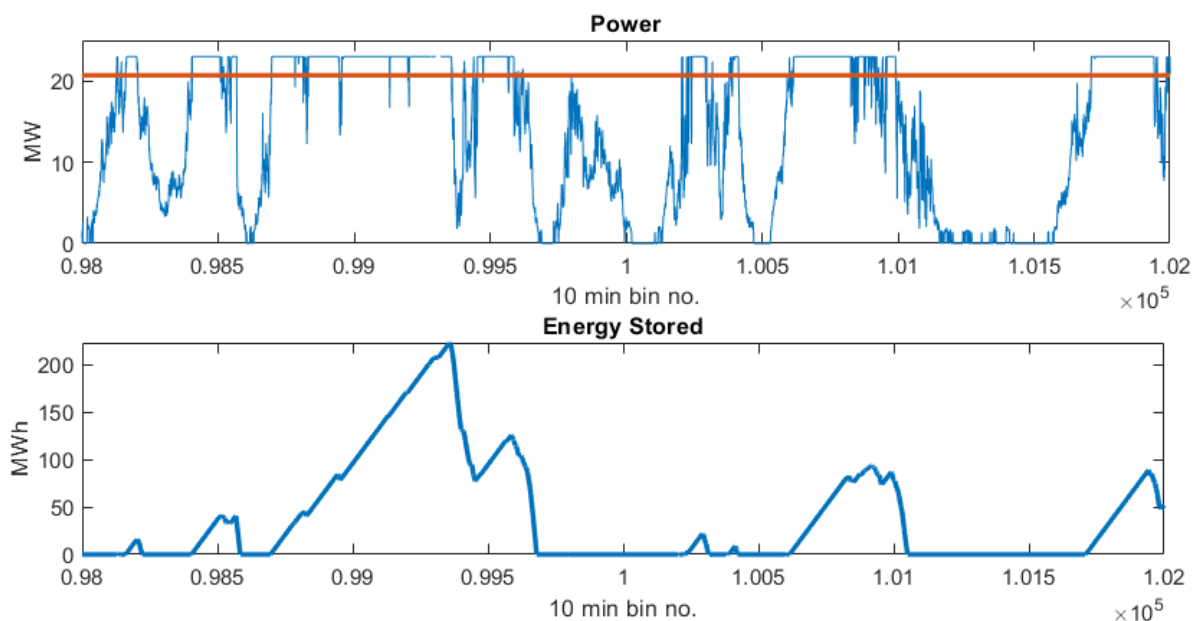


Figure 3. Power and required energy storage from a de-rated cable

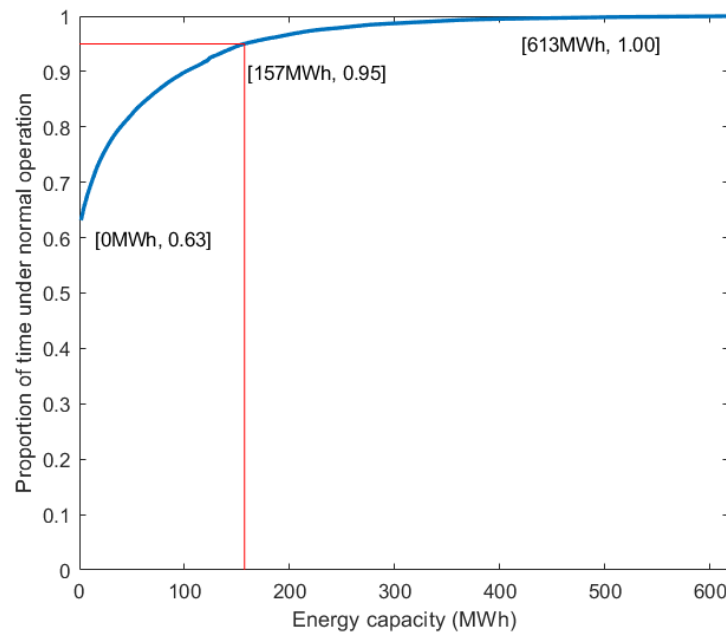


Figure 4. Confidence level of ESS capacities

3. Results and discussion

3.1. Turbine placement optimisation

Figure 5 shows the real world layout of the Lillgrund OWF with turbine positions and the power loss due to wake interactions within the wind farm. It can be seen that immediately next to a turbine the power loss due to the turbine wakes would be very large should another turbine be placed nearby. As the predominant wind direction is from the west (heading east), the summation of the effects of the wakes can be seen in the areas between turbines. On the western edge of the wind farm there is virtually no power loss in the areas between turbines however on the eastern edges there is a large overall power loss in the region. The turbines' positions seem to not take this into account being regularly spaced throughout the wind farm resulting in large power losses.

Figure 6 shows the heuristically optimised turbine positions and their combined wake effect throughout the wind farm. Turbines are placed near the edges of the wind farm, and the forbidden region, to take advantage of the reduced wake effect there - particularly along the western border where the predominant wind direction meets the wind farm. In the central region of the farm the turbines are distributed such that they minimise their pair-wise interference.

The overall result of this quick heuristic improvement is summarised in table 1. Allowing the placement of unlimited turbines, the model is able to place 50 turbines in the wind farm, 2 more than the real site and increasing the rated power of the wind farm. Because of the meteorological conditions and the variation in wind speed at the site, the expected power can be seen as 59.39MW and 61.87MW for the original and optimised sites. Additionally the wake losses are reduced from 20.82% to 18.70% of rated power resulting in mean wind farm power of 36.41MW to 40.36MW. This equates to a capacity factor of 32.98% and 35.10%, for 48 turbines and 50 turbines, respectively, before any operation and maintenance activities are considered - increasing not only the number of turbines in the wind farm but also their efficiency.

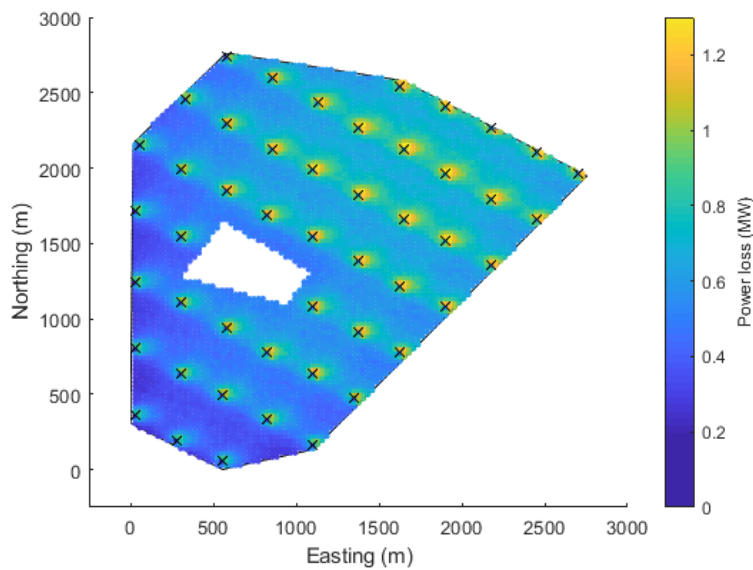


Figure 5. Lillgrund OWF turbine positions without optimisation

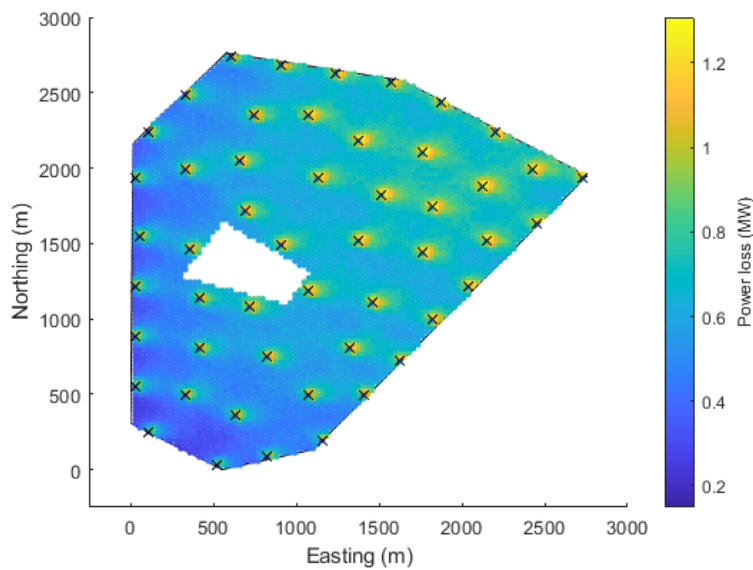


Figure 6. Optimisation results of turbine positions

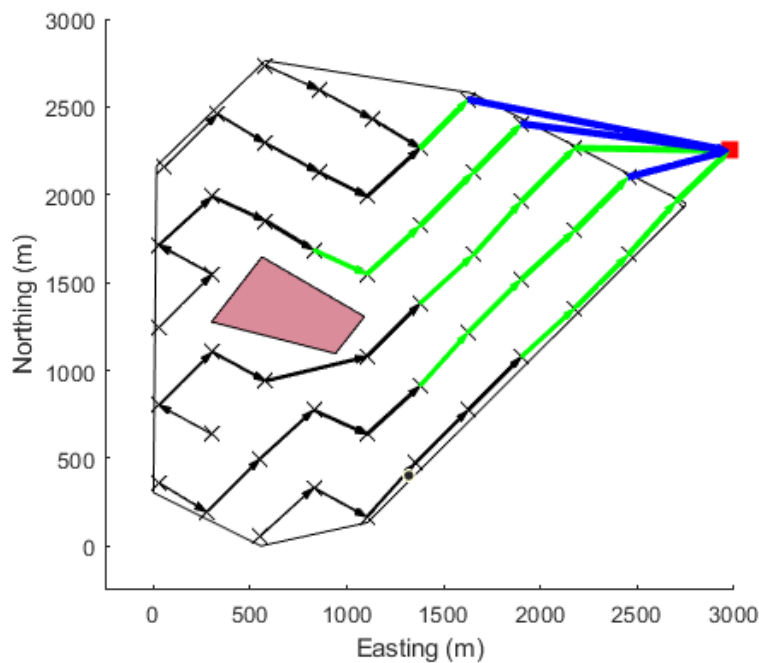
3.2. Cable layout optimisation

As the turbine placement and cable layout phases are separate, it is possible that benefits in turbine placement may lead to increased costs in cable layout. Figure 7 shows the cable connections for the real Lillgrund site, with different cable sizes differentiated by colour. Here a string of turbines is connected, with each section using the minimum necessary cable size to reduce CAPEX. Figure 8 shows the newly optimised site containing 50 turbines and the cable connections used. In order to be comparable, the same types of cable were used as in the real site: these can be seen coloured as in figure 7.

The MILP solver runs very quickly, performing the pre-processing in around 20 seconds

Table 1. Wind farm power

	Original	Optimised
No. turbines	48	50
WF rated power (MW)	110.4	115.0
WF expected power (MW)	59.39	61.87
Wake losses (% P_{rated})	20.82	18.70
WF mean power (MW)	36.41	40.36
Capacity factor (%)	32.98	35.10

**Figure 7.** Lillgrund OWF cable layout

and the optimisation in approximately 6 minutes on a standard desktop PC. The costs of the two cable layout configurations are summarised in table 2. The total cost of the real site is estimated to be approximately £63.13M, comprised of £11.87M of cable unit and installation cost and £51.26M of electrical losses over a 25 year project life in net present value. The new site, with 50 turbines, can be seen to have a total electrical collector network cost of £50.75M, a reduction of £12.38M. It can be seen that - due to many more turbines being connected with larger, more expensive cables - the CAPEX component increases by around £3.5M but the reduction in electrical losses over the lifetime of the project far offsets this, resulting in an overall cost reduction.

4. Conclusions

The quick heuristic optimisation improved on the Lillgrund OWF design, introducing 2 additional turbines to the farm while also increasing the overall wind farm efficiency. At utility

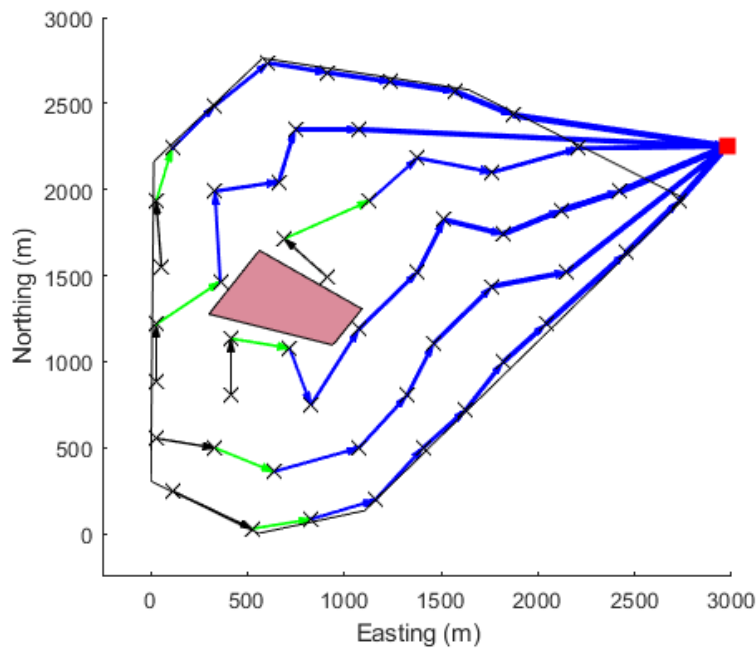


Figure 8. Optimisation model cable layout

Table 2. Cable layout

	Original	Optimised	Change
Cable cost (£M)	11.87	15.40	+3.53
Electrical losses (£M)	51.26	35.35	-15.91
Total cost (£M)	63.13	50.75	-12.38

scale, small improvements in output power can lead to large increases in revenue, a reduction in LCOE and enable the wind farm to be more competitive in bidding processes. Although the heuristic algorithm is very fast to run, the pre-processing of these problems can be very time consuming. This is in large part due to the resolution of the wind farm, n , in the discretisation stage where the number of equations generated are of the order $O(n^2)$. For this case, the resolution could be greatly reduced without too much effect on the result, as the distance between nodes was approximately one quarter of the rotor diameter.

With the newly positioned turbines the cable layout optimisation demonstrated that the layout improvements were not necessarily at the expense of the collector network cost. Indeed, the cable layout optimisation solution showed an increase in CAPEX but a greater reduction in electrical losses over the lifetime of the project leading to a large overall reduction in collector network costs. This process could equally be performed on the real world turbine positions to provide cost savings, however this was not covered in the study.

Energy storage may have the potential to further reduce cable costs by allowing for the continued operation of a wind farm under a de-rated, cheaper collector network. However, simple analysis of a representative power time series shows that, with the desired level of de-rating described previously, the capacity of the ESS would quickly become prohibitively large.

A possible solution to this, is to introduce intermediate cable sizes to allow for a smaller change in cable capacity and therefore reduce the necessary ESS size. Alternatively, using the ESS for ancillary services when it is not required for power smoothing may provide the necessary revenue to make this solution cost effective.

4.1. Future improvements

With two independent optimisation phases it is possible that the first may improve at the expense of the second and so may miss a 'more-optimal' trade off found if the two optimisations were integrated processes. As such, a useful future investigation may be to run the two models above with the addition of a feedback loop in order for the turbine positions to be influenced by the likely cable layout of that solution. Secondly, as the above turbine placement solution removes the regular grid-based structure of the wind farm, issues with navigation and search and rescue may be introduced. A solution to this may be in a grid-based optimisation algorithm to maintain the grid-based structure while finding some of the benefits to wind farm power and profitability.

Acknowledgments

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